Coupled Dynamics of the Wave-Atmospheric Boundary Layer at Strong Winds

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LONG-TERM GOALS

The main goal of the proposed research is to study theoretically the role of the breaking wind waves and the sea spray, generated by them, under strongly forced situations in the airflow dynamics in particular in energy, momentum, heat and moisture transfers through the sea surface. Through this to increase the knowledge of the air-sea interaction and to apply this knowledge for developing improved, physics-based parameterizations of the fluxes (momentum, energy, heat and moisture) in the wave-coupled atmospheric boundary layer. The proposed study is essential to quantify the wave breaking effects on surface transfers, especially in the case of strong winds, where the sea spray generated by breaking waves is believed to play the dominant role in the airflow dynamics. The improved surface forcing (parameterizations of fluxes) is aimed at improvement of the performance of the high-resolution wave and coupled atmosphere-ocean models. The principle innovation of this study is that the airflow and wind waves are considered as a self-consistent interacting coupled system, where the properties of the sea surface (shape of the wave spectrum, wave breaking statistics, etc.) and turbulent characteristics of the atmospheric wave boundary layer are interrelated with each other.

OBJECTIVES

The effect is devided into 4 Tasks.

Task 1. Effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness.

Objectives Task 1. Development of a generalized model relating the aerodynamic roughness and the surface fluxes to the statistical properties of the sea surface, which can be uniformly adopted in the Marine Atmospheric Boundary Layer (MABL) model for any sea state (developed and developing waves, swell and mixed seas) and wind (from calm to hurricane) conditions. To study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness)

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at high wind conditions. To study the impact of the airflow separation on the near surface turbulence and turbulent momentum flux and implementation of results into the existing Wind-Over-Waves Coupling (WOWC) model. To combine the existing drag-swell (SWELL) and extended WOWC models in one unified model tool describing the sea surface and the near surface turbulent fluxes in a wide range of sea state and wind conditions.

Task 2. Development of a model of the spume droplets production.

Objectives Task 2. Development of a theoretical model of the spume droplets generation, which relates the rate of the spume droplets production and distribution of droplets over size to the wave breaking statistics, sea state conditions and the wind speed. To compare the model results with existing and new High-Resolution Wave-Air-Sea Interaction DRI experimental data.

Task 3. Investigation of the impact of sea droplets on the structure of the MABL and the exchange processes at the sea surface at strong wind conditions.

Objectives Task 3. Development of a MABL model coupled with waves that is valid in a wide range of the wind speed conditions, up to the wind of a hurricane force. To investigate the effect of sea droplets on the atmospheric turbulence, turbulent fluxes, wind profile through their impact on the buoyancy force and the spray stress. To investigate how the sea spume droplets and the airflow separation are tied together in setting of momentum, heat and moisture fluxes at the sea surface. Establishing new parameterizations of the sea surface transfer coefficients, and the parameters of the lower atmosphere like sea droplets concentration aiming at use and improvement of the wave/atmospheric/upper-ocean modeling including hazardous wind conditions.

Task 4. Testing of the model development on the dedicated DRI experiments and application of the model approach for the experimental data analysis.

Objectives Task 4. Application of the WOWC, SWELL, MABL, newly developed WOWC-SWELL and MABL-WOWC models for the interpretation of the High-Resolution Wave-Air-Sea Interaction DRI experiments.

APPROACH

The study is based on the Wind-Over-Waves Coupling theory/model developed by the offerors in the last decade. WOWC is a modern theory/model of microscale air-sea interaction, which allows relating the sea drag (surface stress) directly to the properties of wind waves and peculiarities of their interaction with the wind (Makin, 1998, 2005; Makin et al. 1995; Makin and Kudryavtsev, 1999, 2002, 2003; Kudryavtsev et al., 1999; Kudryavtsev and Makin, 2001, 2002). The WOWC model is based on the conservation equation for integral momentum, which relates the friction velocity to the surface stress supported by viscous stress and the form drag. The form drag is supported by the wave-induced stress and by stress due to separation of the airflow from breaking wind waves. The theory provides a clear understanding of the physical mechanisms forming the surface stress, and an explanation on what causes the stress dependence on the wind speed, wave age, finite bottom depth, and other ocean and atmosphere parameters. Thus the research combines a theoretical/modeling approach to describe the air-sea interaction in the full range of wind speeds including extreme winds with the use of existing and new field and laboratory data for a model validation and interpretation of the experiments. It will

utilize the knowledge to be obtained in parameterizations of the sea surface exchange processes, the sea drag coefficient in the first place.

The experimental effort, which underpins the present DRI, and the theoretical analysis of its results, which is offered by the present research effort, are deeply interrelated. On one side, the experiment will provide new data to check theoretical assumptions of the model. On the other, the WOWC model directly relating the surface exchanges, momentum flux in the first place, to the properties of the sea surface and its interaction with the airflow allows a clear physical explanation how the sea surface stress is formed and regulated by the surface phenomena. Waves play in that processes the dominant role. The WOWC model was successfully applied to predict stresses in a wide variety of low to moderate wind speeds and sea-state conditions. At strong wind speeds actively breaking waves and corresponding sea spray and foam production could significantly change the exchange processes.

Focusing on investigation of the air-sea interaction at high winds the WOWC model will be extended to account for the impact of the separation on the aerodynamic roughness of the sea surface by the intensive sheltering of the sea surface by separation bubbles, and the impact of the spume droplets, generated by intensively breaking waves, on the structure of the MABL including surface exchanges.

An experiment, although is an ultimate truth, is hardly able to separate effects of the multiple influences involved in the coupled system ocean-waves-atmosphere. This can be done within the theoretical/numerical models, by switching on and off different physical mechanisms. If, for particular conditions, the experiment and the model produce identical or close results, we assume that physics included in the model is adequate for the relevant field circumstances. If, on the contrary, there are essential discrepancies between the measurement and the model, such cases will be scrutinised to find the cause.

PI Dr. Vladimir Makin (KNMI) and Co-PI Prof. Vladimir Kudryavtsev (RSHMU) are the key individuals participating in this work. They coordinate the effect, develop theoretical ideas of the research, and participate in models construction and modeling. They participate in the analysis of model results and comparison studies with experimental data.

WORK COMPLETED

Task 1 to study the effect of wind waves and swell on the surface fluxes in the range of wind speeds from calm to very strong when the airflow separation from breaking wave crests dominates the aerodynamic surface roughness with the objective to study the effect of the airflow separation from breaking waves on the form drag of the sea surface (aerodynamic roughness) at high wind conditions is completed.

Task 2 to develop a theoretical model of the spume droplets generation, which relates the rate of the spume droplets production and distribution of droplets over size to the wave breaking statistics, sea state conditions and the wind speed is completed.

Task 3 to develop a MABL model coupled with waves that is valid in a wide range of the wind speed conditions, up to the wind of a hurricane force is completed. A subtask to investigate the effect of sea droplets on the atmospheric turbulence, turbulent fluxes, wind and droplets concentration profiles through their impact on the buoyancy force and the spray stress is completed

RESULTS (achieved in the report fiscal year)

Wind excites waves on the ocean surface .With increasing wind speed waves begin to break intensively and generate ocean spray- small droplets of water that are then transported upwards into the atmosphere The impact of ocean spray on the dynamics of the marine atmospheric surface boundary layer (MABL) in conditions of very high (hurricane) wind speeds is investigated. To that end a model of the MABL in the presence of sea spume droplets is developed. The model is based on the classical theory of the motion of suspended particles in a turbulent flow, where the mass concentration of droplets is not mandatory small. A description of the spume droplets generation assumes that they, being torn off from breaking waves, are injected in the form of a jet of spray into the airflow at the altitude of breaking wave crests. The Droplets affect the boundary layer dynamics in two ways: via direct impact of droplets on the airflow momentum forming the so-called "spray force", and via the impact of droplets on the turbulent mixing through stratification. The latter is parameterized applying the Monin-Obukhov similarity theory. It is found that the dominant impact of droplets on the MABL dynamics appears through the action of the "spray force" originated from the interaction of the "rain of spray" with the wind velocity shear, while the efficiency of the stratification mechanism is weaker. The effect of spray leads to the suppression of the turbulent wind stress in the MABL and, as a consequence, to the acceleration of the wind velocity and suppression of the sea surface drag.

The key issue of the model is a proper description of the spume droplets generation. It is shown that after the spume droplets generation is fitted to the observations, the MABL model is capable to reproduce the fundamental experimental finding - the suppression of the surface drag at very high wind speeds. We found that at very high wind speeds a thin part of the surface layer adjacent to the surface turns into the regime of limited saturation with the spume droplets resulting in the leveling off of the friction velocity and decrease of the drag coefficient as U^{-2}, where U is the wind speed at 10 m height.

This dependence of the drag coefficient was parameterized and tested in an atmospheric circulation model. In numerical weather prediction (NWP) models the stress at the air-sea interface is computed according to the bulk flux relation, which involves a formulation for the drag coefficient. Computation of the drag coefficient is commonly based on the Charnock relation. Then, a monotonic increase in the drag coefficient for increasing near-surface wind speeds is predicted. Recent observations, however, have indicated that the magnitude of the drag coefficient levels off at a certain 10-meter wind speed, of approximately 30 m/s, and decreases with further increase of the wind speed. Thus, usually the magnitude of the drag coefficient in NWP models is too large. As a result the intensity of hurricanes is often underestimated in forecasts. In this study a drag parameterization that predicts the decrease in sea drag from a 10-meter wind speed of about 28 m/s is tested in the NWP model HIRLAM. The parameterization is based on the formation of a suspension layer above the air-sea interface in which the atmospheric flow is affected by spray droplets. Two hurricanes from the last few years are modeled with HIRLAM: Ivan (2004) and Katrina (2005). The results show that, compared to the common Charnock relation, the use of this drag parameterization leads to much stronger hurricanes in forecasts. The results show good agreement with observations.

Field measurements of the swell-induced undulation of the wind speed taken from a Black Sea platform were obtained. The wind speed and its fluctuations were measured at several heights between 1.3 and 21 m above the mean sea level under various wind and swell conditions. Parameters of the swell-induced undulations were derived from cross spectra of the wind-speed fluctuations and the sea-surface displacement. As found, the phase and the amplitude of the wind speed undulation in the layer from $kz = 0.1$ to $kz = 3$ (k is the swell wavenumber) are in good agreement with the theory of inviscid

shear flow over a wavy surface. The main feature of the vertical profile of the swell-induced undulation is the exponential attenuation of its amplitude with height typical for the potential flow over the fast running waves. At the lowest levels the potential undulations are significantly distorted by the wind-speed variations caused by the vertical displacements of the shear airflow relative to a fixed sensor. No direct impact of swell on the mean properties of the turbulent boundary layer at $kz > 0.1$ is revealed. In particular, the mean wind-speed profile and spectra of the horizontal velocity in the inertial sub range obey Monin-Obukhov similarity theory.

IMPACT/APPLICATIONS

The main innovation of the project is the development of the advanced model describing the exchange processes at the sea surface in extreme wind conditions. This covers the improved description of the sea surface and the WOWC model, and assessment of the sea spray role in the momentum flux above the sea. The project will provide new knowledge and parameterizations of the sea surface fluxes, which will be valid for the whole range of wind speeds and sea surface conditions and can be used as improved boundary conditions for high-resolution numerical models of ocean, atmosphere, and coupled ocean-atmosphere systems, and covers all spatial and temporal scales from local high-resolution to global climate studies. Therefore, this study directly addresses social needs to improve climate variation predictions, weather forecasts and to reduce the impact of natural hazards caused by extreme wind and sea-state conditions.

RELATED PROJECTS

PhD research “Air-sea interaction and sea-state forecasts in extreme weather conditions”, 2007-2011, funded by Netherlands Organization for Scientific Research. The main goal of this research is to apply consistently new parameterizations of the sea drag to the sea state and atmosphere models with focusing at extreme weather conditions and aiming at models improved performance. Parameterizations, which will be obtained in the course of the DRI effort, are obvious candidates for the testing.

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